Electrostatic Discharge Test of Multi-Junction Solar Array Coupons after Combined Space Environmental Exposures

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A set of multi-junction GaAs/Ge solar array test coupons were subjected to a sequence of 5-year increments of combined environmental exposure tests. The test coupons capture an integrated design intended for use in a geosynchronous (GEO) space environment. A key component of this test campaign is conducting electrostatic discharge (ESD) tests in the inverted gradient mode. The protocol of the ESD tests is based on the ISO/CD 11221, the ISO standard for ESD testing on solar array panels. This standard is currently in its final review with expected approval in 2010. The test schematic in the ISO reference has been modified with Space System/Loral designed circuitry to better simulate the on-orbit operational conditions of its solar array design. Part of the modified circuitry is to simulate a solar array panel coverglass flashover discharge. All solar array coupons used in the test campaign consist of 4 cells. The ESD tests are performed at the beginning of life (BOL) and at each 5-year environment exposure point. The environmental exposure sequence consists of UV radiation, electron/proton particle radiation, thermal cycling, and ion thruster plume. This paper discusses the coverglass flashover simulation, ESD test setup, and the importance of the electrical test design in simulating the on-orbit operational conditions. Results from 5th-year testing are compared to the baseline ESD characteristics determined at the BOL condition.

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UAHuntsville
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

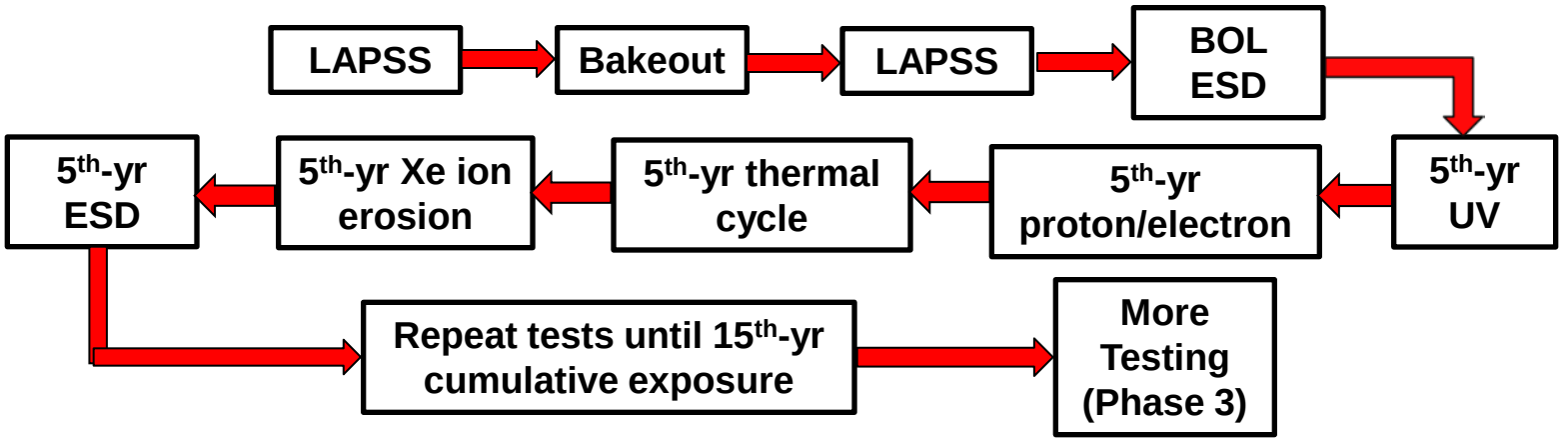
NASA

SPACE SYSTEMS
LORAL

Combined Environment Test Program - Outline

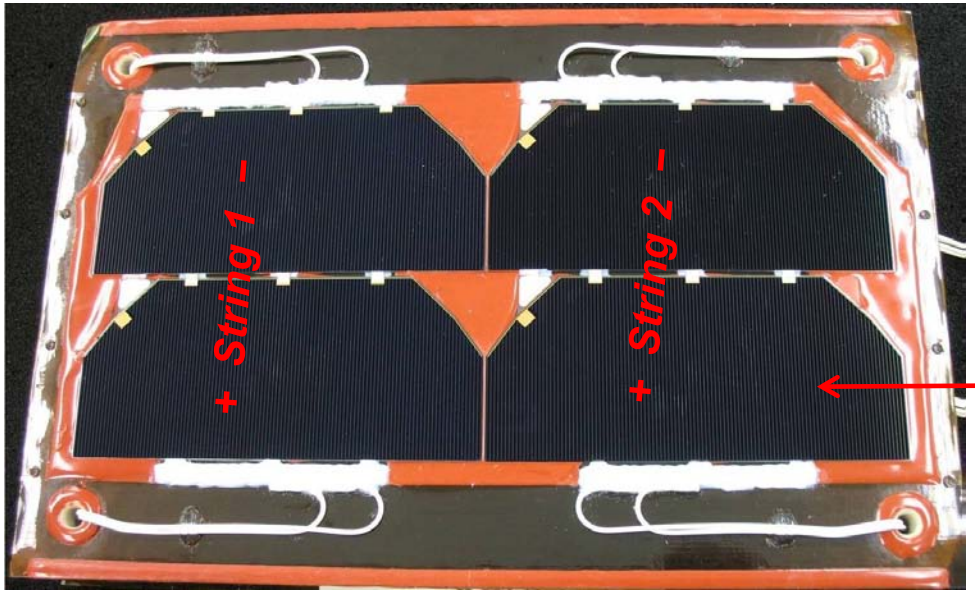
- ***A set of multi-junction GaAs/Ge solar array test coupons are currently being subjected to a sequence of 5-year increments of combined environmental exposure tests.***
  - ✓ ***ESD → UV radiation → electron/proton particle radiation → thermal cycling → ion thruster plume – all at the NASA/Marshall space Flight Center***
- ***Further details of this multi-phase test program are discussed in the poster paper entitled "Combined Space Environmental Exposure Tests of Multi-junction GaAs/Ge Solar Array Coupons" by Hoang et al.***

Planned Sequence (Phase 2):



Test Coupon Description

- ***4 Emcore ATJ cells: 2 strings with 2 cells/string. Cell area = 30.49 cm^2.***
- ***Coverglass - Qioptiq CMG, 100-µm thick with a single-layer MgF_2 anti-reflective coating.***
- ***Each solar cell assembly (SCA) has a discrete Silicon bypass diode.***
- ***3 coupons used in test program (designated as A, B, and C)***



For Coupon C, this cell is intentionally repaired

ESD Test: Outline

- ***ESD tests are performed at Beginning-of-Life (BOL), 5-year, 10-year, and 15 year (End-of-Life)***
- ***Uses guidelines from ISO-11221***
- ***Each coupon is tested in the inverted gradient condition (discussed in a later slide)***
- ***Testing with primary arc simulation***
  - ✓ ***Limited quantity of arcs through test program motivated by study of SS/L GEO satellites and number of arcs***
    (Cho et al., Number of arcs estimated on solar array of a geostationary satellite, J. Spacecraft and Rockets, Vol. 42, No. 4, July – August, pp. 640-748, 2005.)
  - ✓ ***Two conditions are tested for the differential string voltage: 55 V/0.55 A and 108 V/0.55 A.***

ESD Test: Allowable Arc Count

Threshold Test

Test	Room Temp	Cold Temp -10C	Cold Temp -40C	Cold Temp -70C
BOL ESD	2	2	2	2
5th-year ESD	2	2*	2*	2*
10th-year ESD	2	2*	2*	2*
15th-year ESD	2	2	2	2

**** Only performed if cold testing required each cycle due to arc threshold voltage change at ambient temperature***

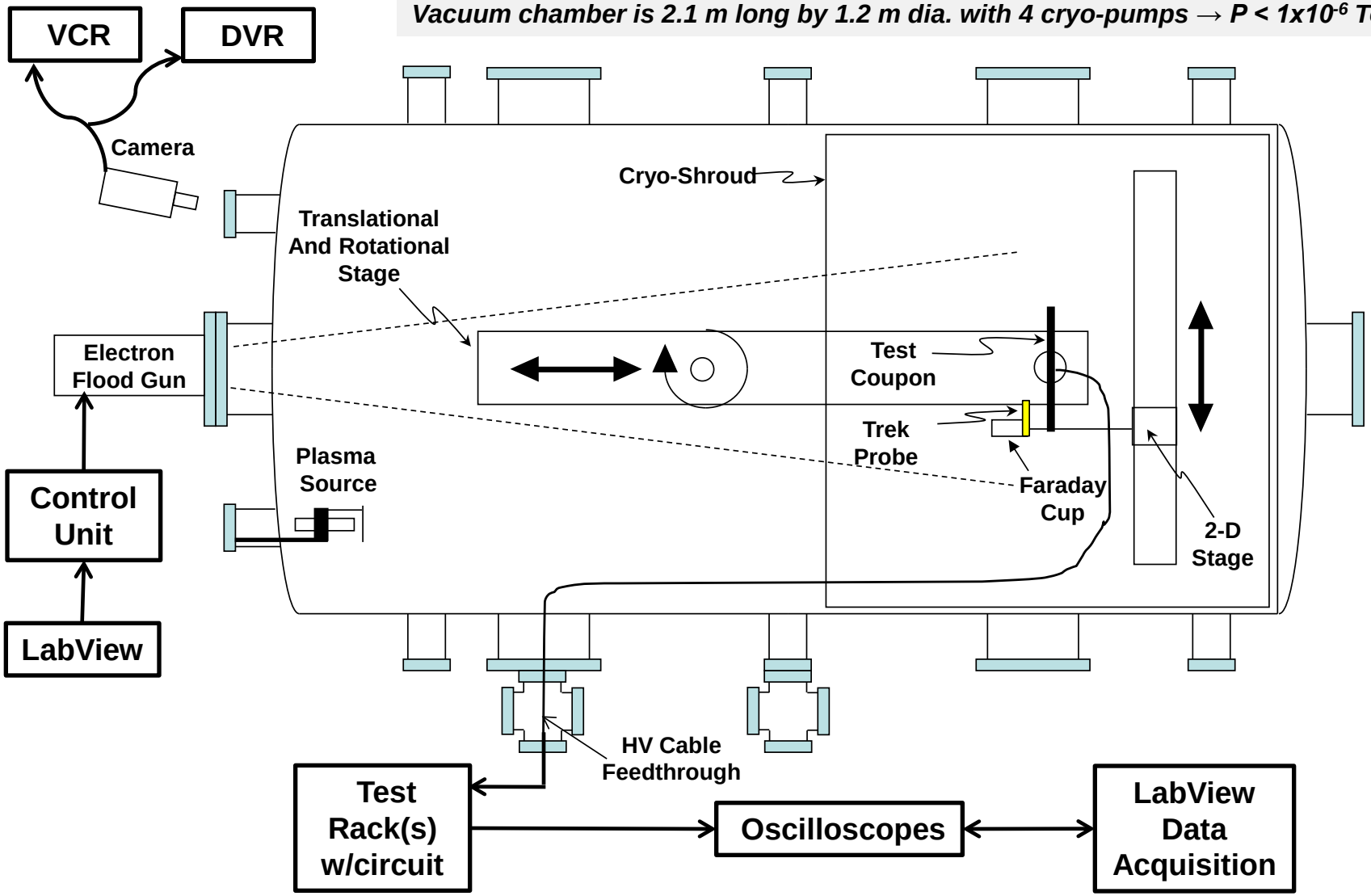
ESD Test

Test	Room Temp	Cold Temp	Room Temp *	Cold Temp*
BOL ESD 54V/0.55A	5	5	3	4
BOL ESD 108V/0.55A	5	5	3	4
5th-year ESD 54V/0.55A	5	0	3	4
5th-year ESD 108V/0.55A	5	0	3	4
10th-year ESD 54V/0.55A	5	0	4	4
10th-year ESD 108V/0.55A	5	0	4	4
15th-year ESD 54V/0.55A	5	5	4	4
15th-year ESD 108V/0.55A	5	5	4	4

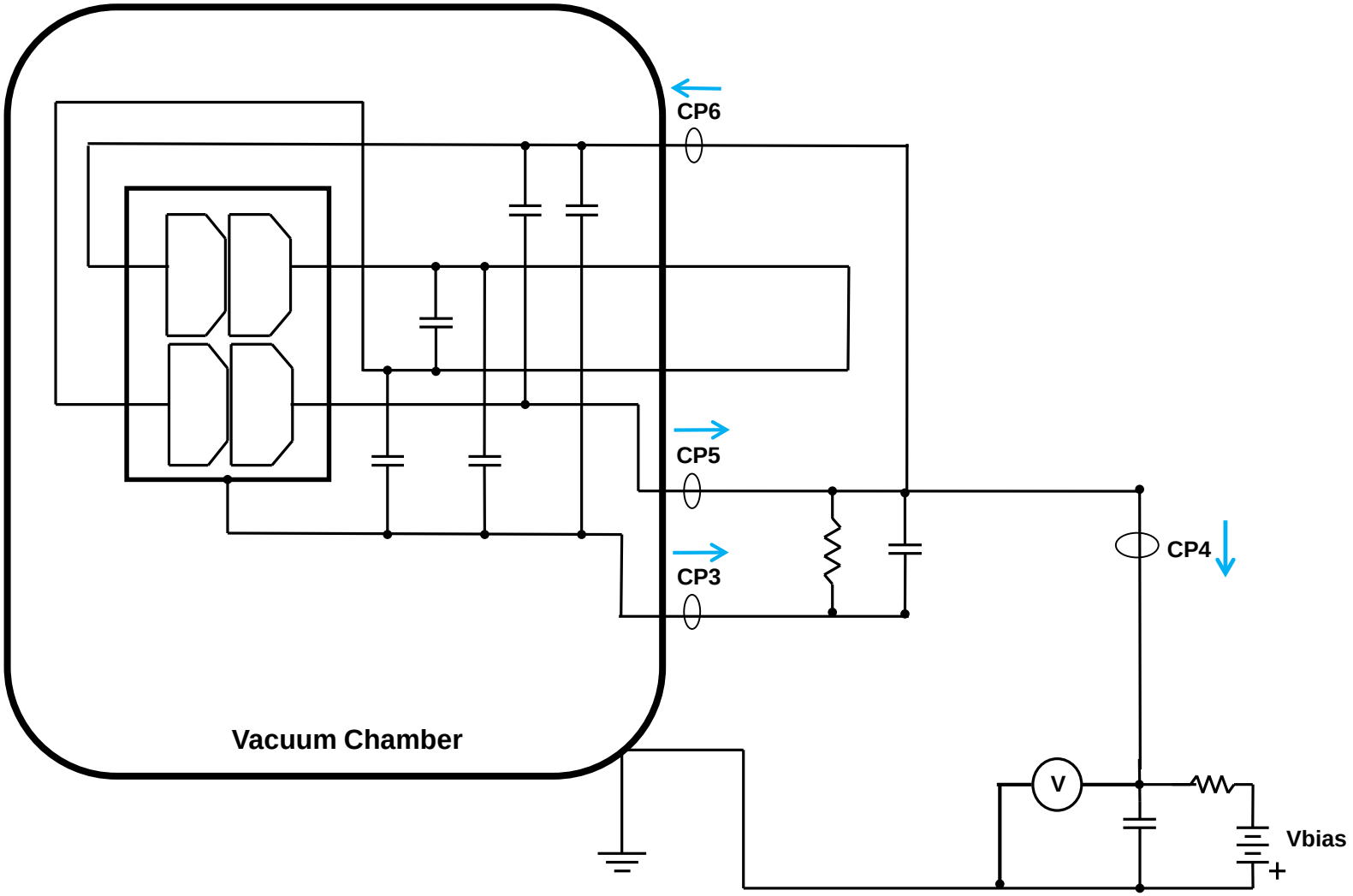
Total number over life of testing = 60

Test Setup Description

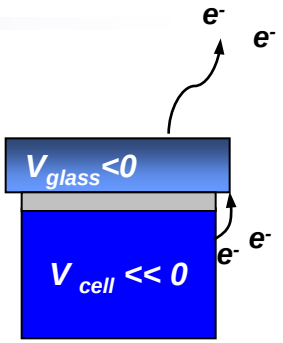
Vacuum chamber is 2.1 m long by 1.2 m dia. with 4 cryo-pumps → P < 1x10^{-6} Torr



Arc Threshold Test Circuit



Arc Threshold Determination

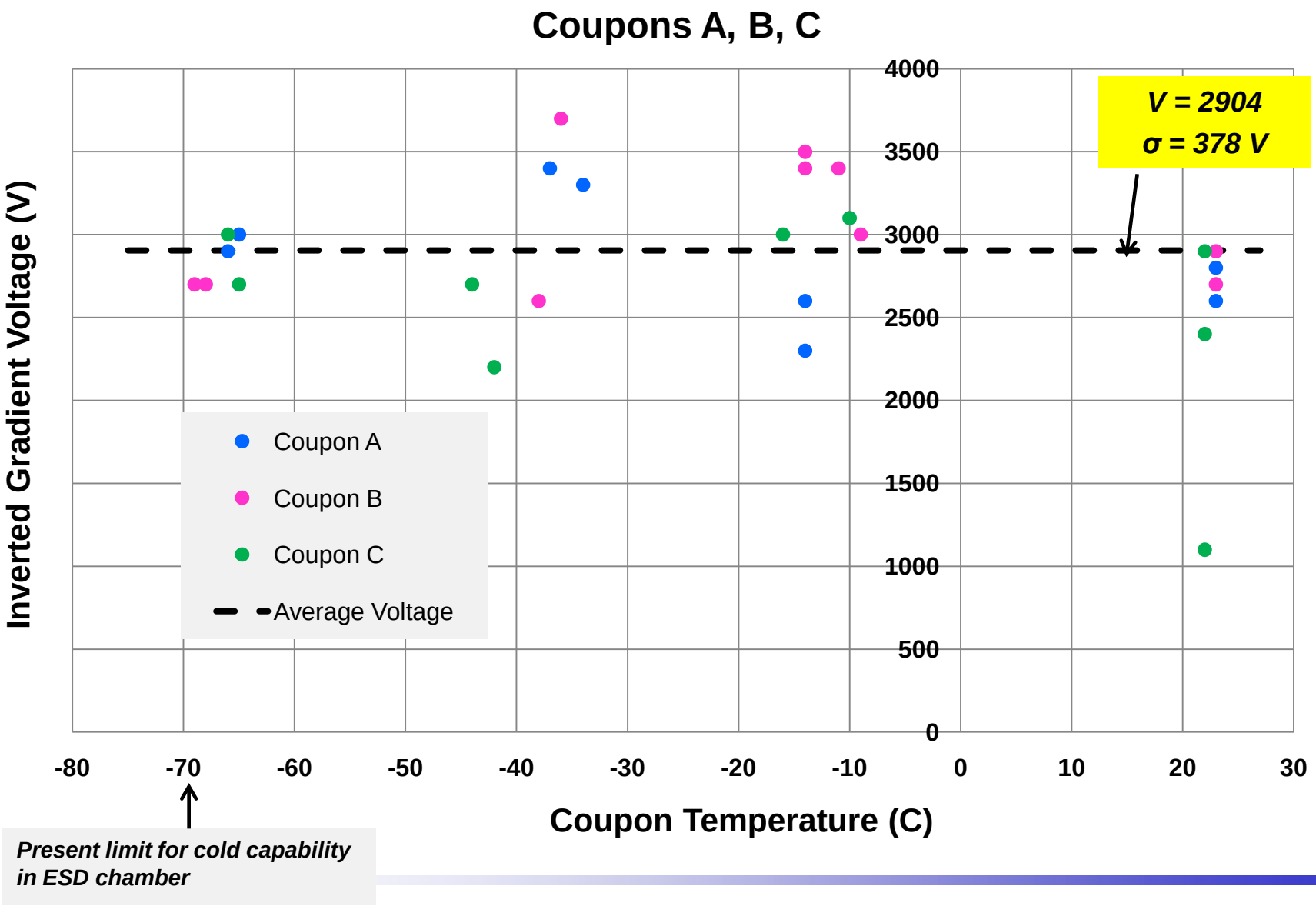


The inverted gradient condition is established by the following:

1) ***Apply -5 kV bias to substrate.***
2) ***With TREK probe, verify that coverglass is at -5 kV.***
3) ***Set electron beam to 5.9 keV.***
4) ***Expose coupon to electron beam flux of 1-2 nA/cm^2 for a limited time.***
5) ***Measure coverglass potential with TREK probe.***
6) ***Set electron beam energy to 900V higher than the magnitude of the coverglass potential.***
7) ***Repeat steps 5-7 until arc occurs.***

We are able to control the change in coverglass surface potential by ~ 200 V through this process.

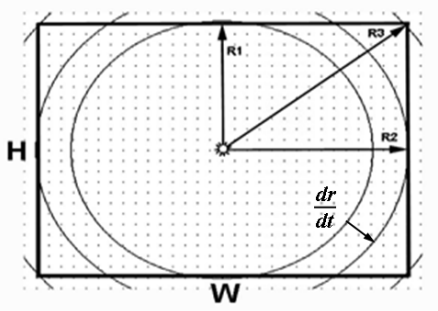
Arc Threshold BOL Results



ESD Test Circuit: Primary Arc Pulse Assumptions

From Hoang et al., Electrostatic discharge test with simulated coverglass flashover for multi-junction GaAs/Ge solar array design, 35th IEEE Photovoltaic Specialists Conference, Honolulu, Hawaii, June 20–25, 2010.

Geometry of Coverglass Flashover from the Center of the Solar Array Panel



Assumptions:

1) ***Coverglass outer surface initially uniformly charged to Voltage (V_c) with respect to solar cell top surface, and discharges by amount deltaV (or V_{th}) during flashover.***
2) ***Flashover current for one panel is assumed to all be collected at a single initiation site.***
3) ***Flashover propagates in a radial surface charge sweep at a constant velocity starting at the initial discharge point.***
4) ***Worst-case peak current is based on complete panel coverglass discharge resulting from a single discharge in the center of the panel. C_{cg} represents the capacitance of the panel coverglass.***
5) ***Flashover terminates at panel edges (R1, R2 and R3) as shown in the figure. Note that R3 ~ 2 meters.***

$$I(t) = \frac{dQ}{dt} = \frac{d}{dt}\left(C_{cg} V_{th} A\right)$$

$$I(t) = C_{cg} V_{th} \frac{dA}{dt}$$

$$\text{where } A = \pi r^2$$

$$I(t) = C_{cg} V_{th} \frac{d}{dt}\left(\pi r^2\right) = 2\pi C_{cg} V_{th} r \frac{dr}{dt}$$

$$\text{where } v = \frac{dr}{dt}$$

With the assumption of constant flashover velocity,

$$I(t) = 2\pi C_{cg} V_{th} v^2 t \qquad \textbf{Eq. (1)}$$

ESD Test Circuit: Primary Arc Pulse Analysis

From Hoang et al., Electrostatic discharge test with simulated coverglass flashover for multi-junction GaAs/Ge solar array design, 35th IEEE Photovoltaic Specialists Conference, Honolulu, Hawaii, June 20–25, 2010.

1) *Flashover propagation velocity, v = 10^4 m/s*
2) *Average measured primary arc threshold voltage of SS/L ATJ array design (~ 2 kV from previous tests)*
3) *Calculated panel coverglass capacitance*
4) *Flashover time to R1, R2 and R3 per Figure on Slide 10, based on the SS/L panel geometry*

From Eq. (1):

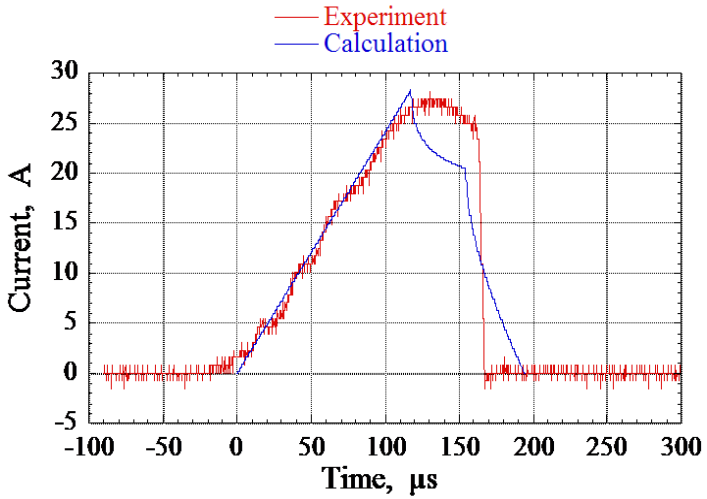
$$I(t_{R1}) = 28.4 Amps$$

(Peak current at R1 as shown in Figure on Slide 10)

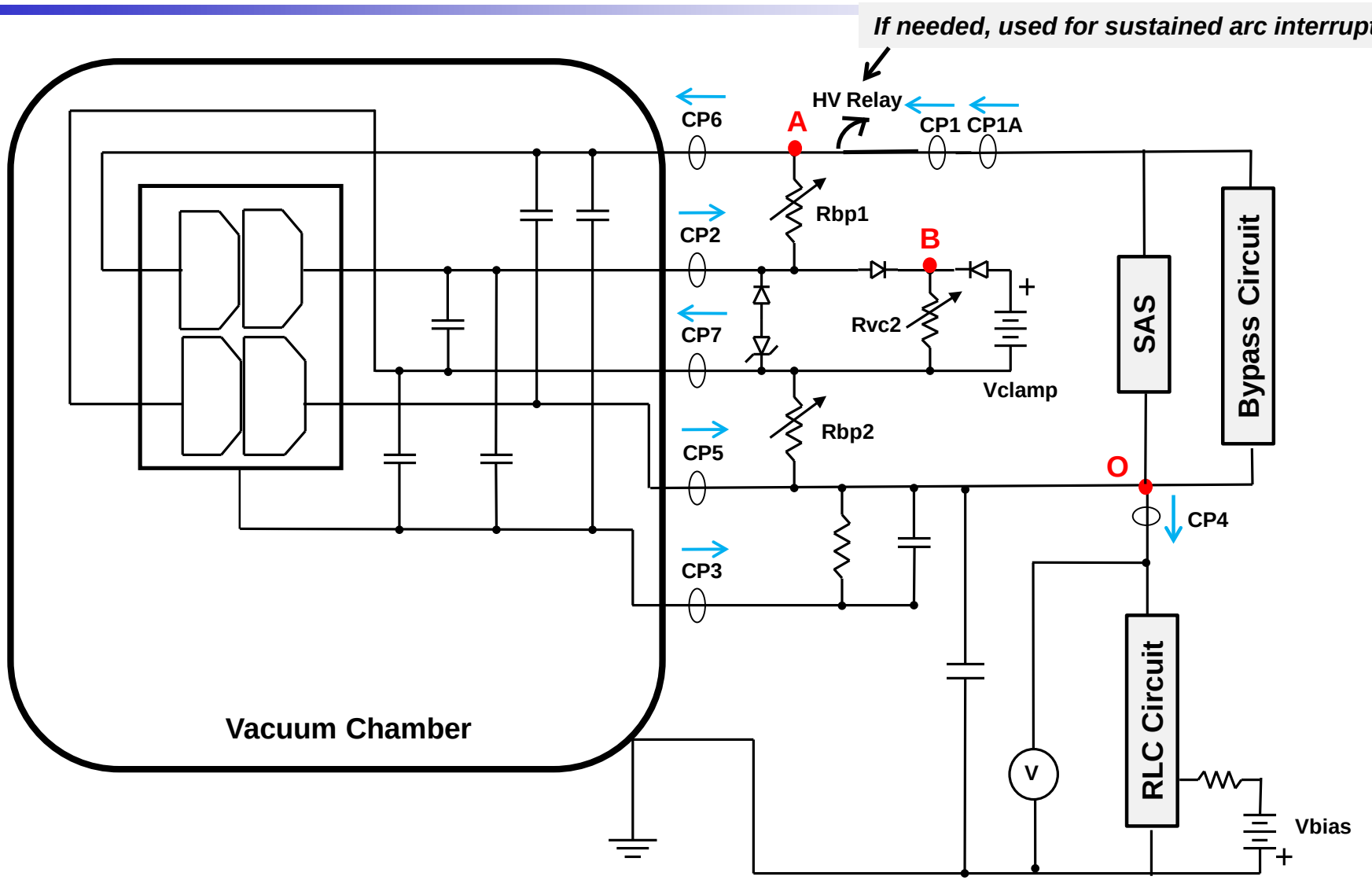
RLC circuit designed to produce waveform that meets three parameters:

1. *Peak current*
2. *Time to peak current*
3. *Total charge of the panel coverglass*

SPICE model calculation compared with measurement:

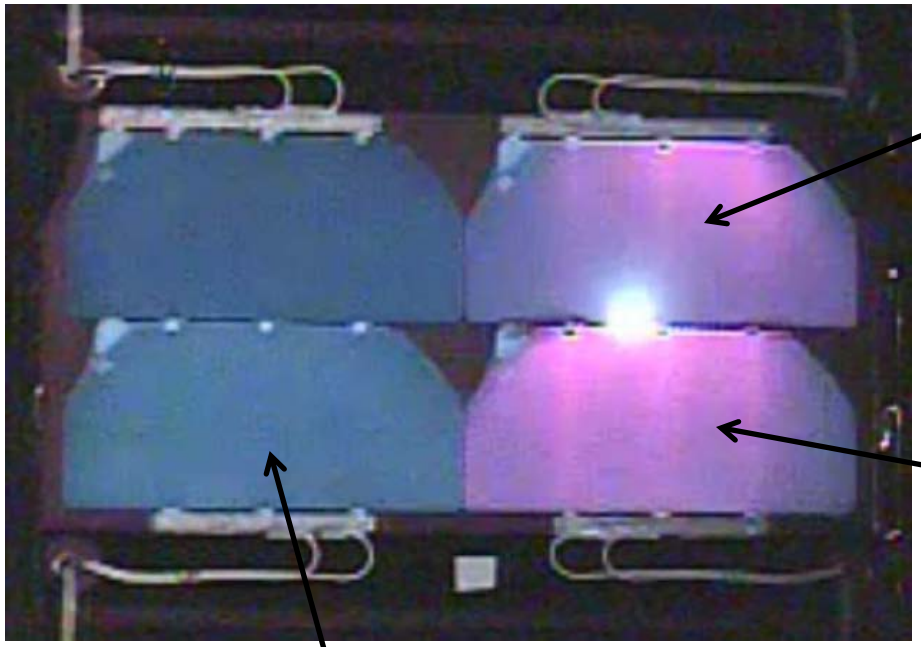


ESD Test Circuit Schematic

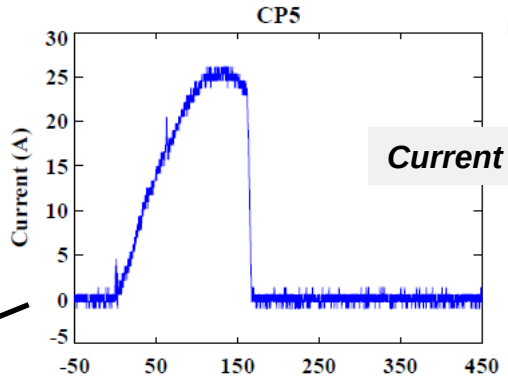


Example of Arc: BOL

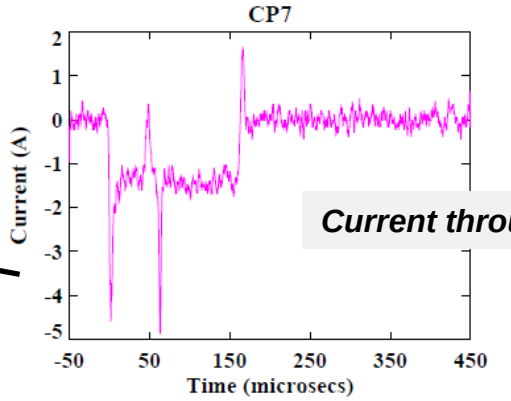
Coupon B: 108V between strings; Temp = -69C; ΔV ~ 3200V



No activity detected on String-1

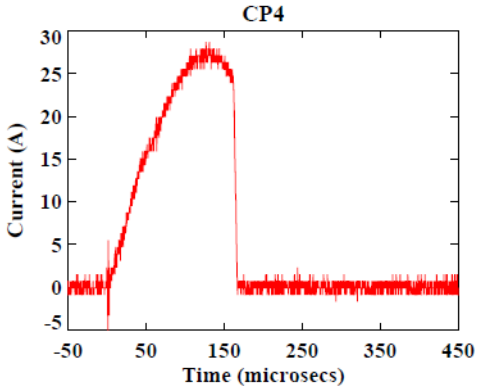


Current through String-2/Cell-2

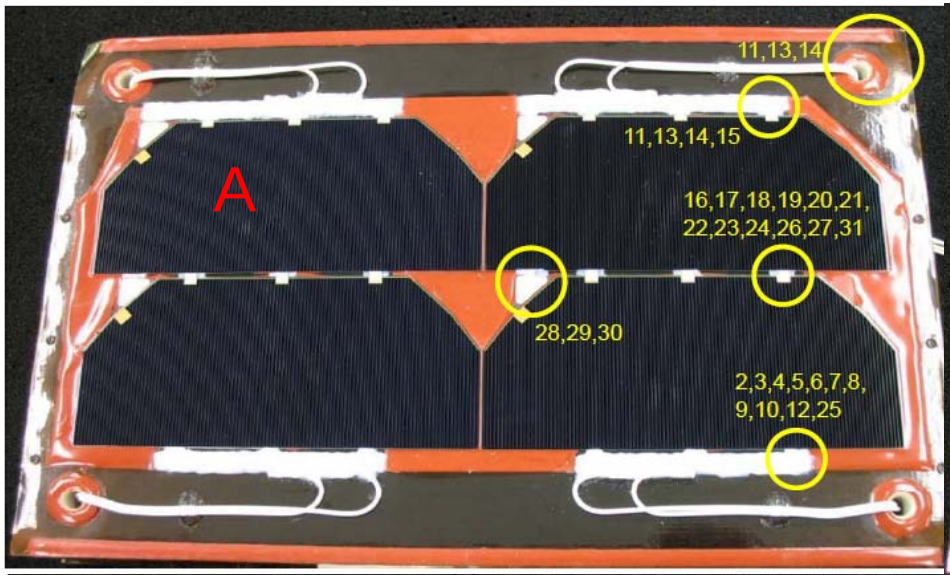


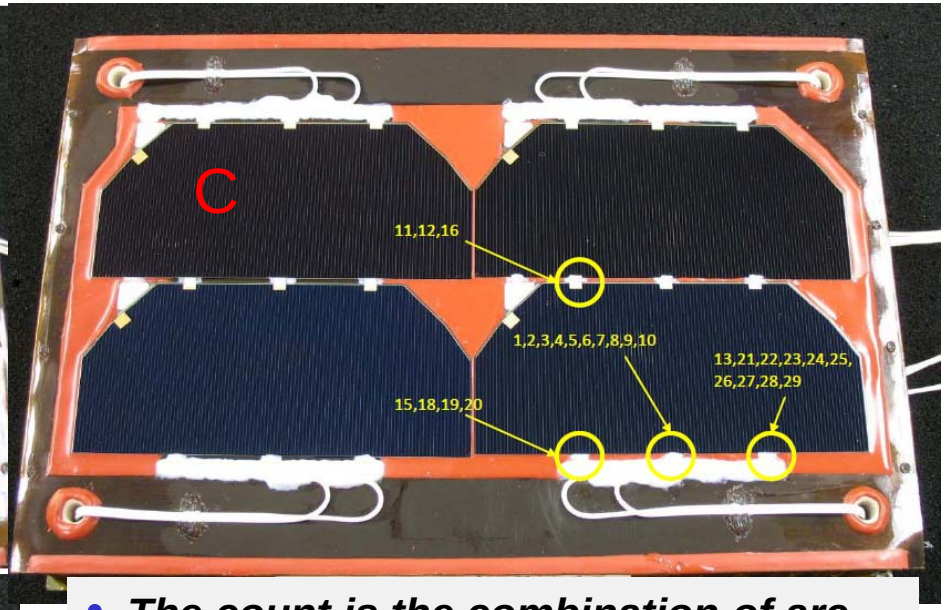
Current through String-2/Cell-1

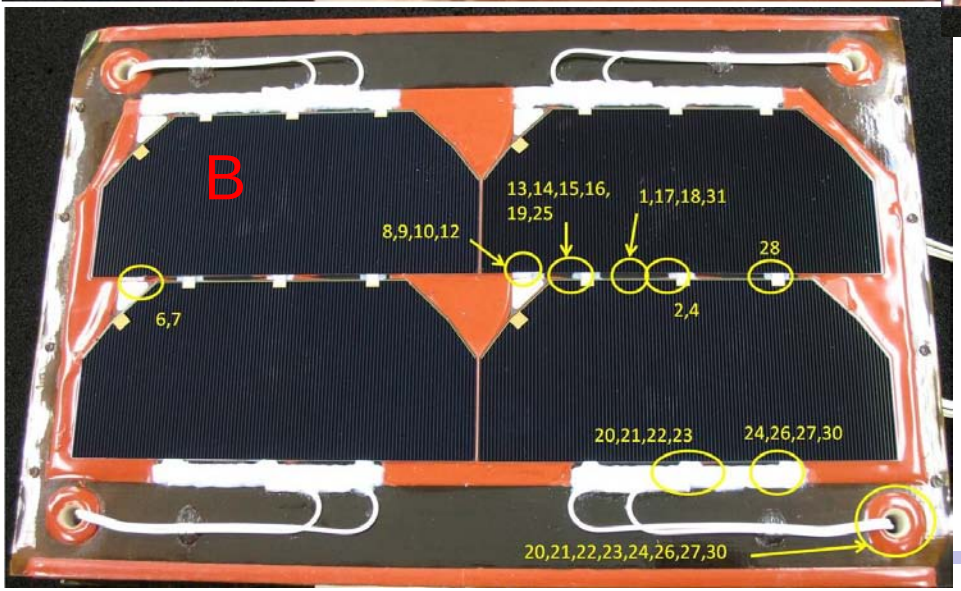
Primary Arc Current



Arc Site Summary: BOL





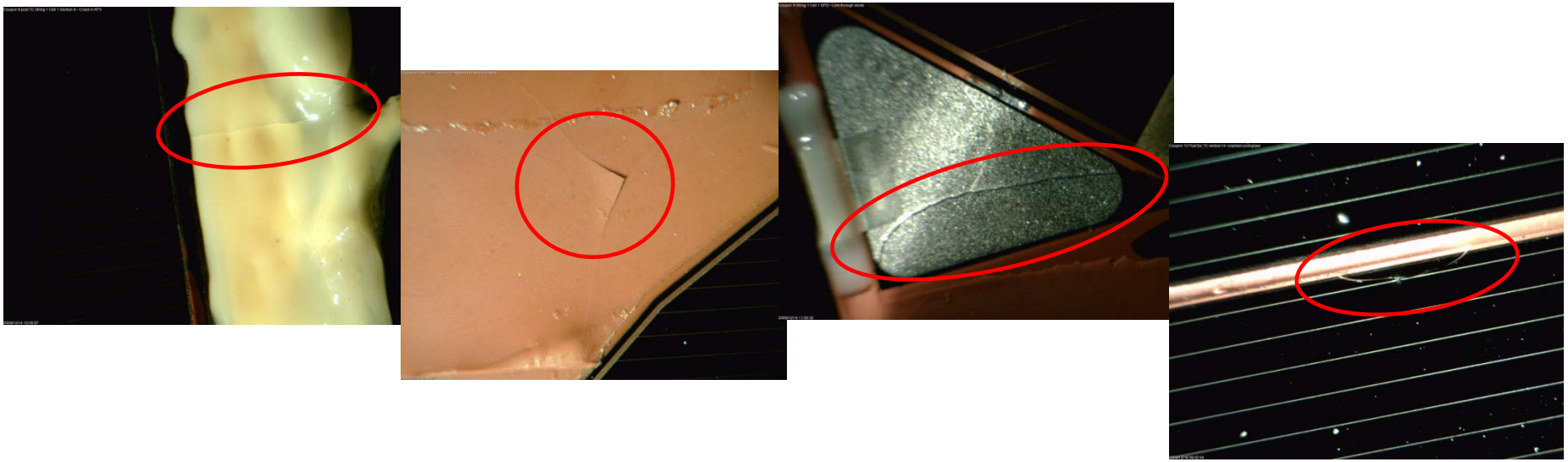


- ***The count is the <u>combination of arc threshold and ESD tests</u>***
- ***Popular arc sites are cell tabs, busbars, and feed-through bushings***
- ***For Coupon C, arc sites favor the reworked cell***

No Temporary Sustained Arcs detected during BOL.

5th-year Test: Status

- ***5th-year UV, proton/electron radiation, and thermal cycling tests have been completed***
  - ✓ ***Inspection has shown various cracks in RTV over tabs and busbars and cracks in the grout between cells. Also, cracks on a few of the cell coverglasses are observed.***

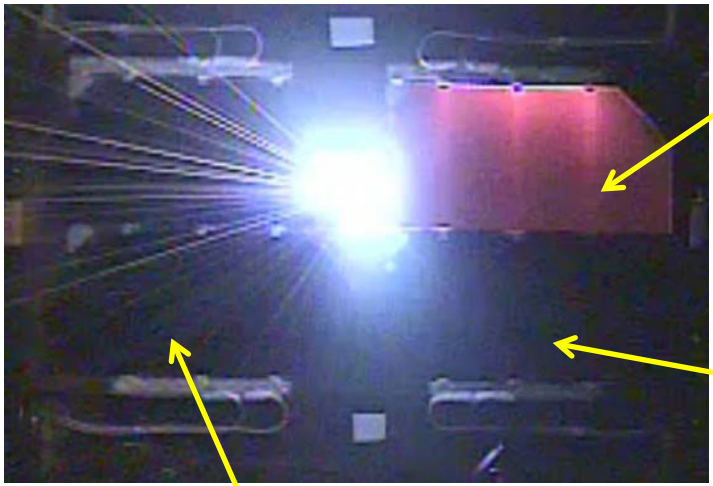


5th-year Test: Status (cont.)

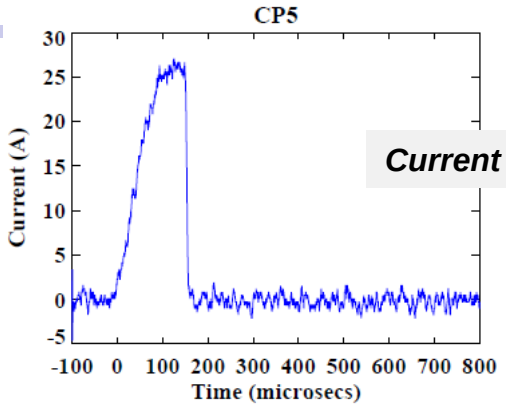
- ***Checkout and verification of an ion source for use in the 5-year Xenon ion erosion test is in work***
- ***A slight alteration in the ESD test plan has occurred – partial ESD testing has been performed on each coupon***
  - ✓ ***The arc threshold voltage for each coupon has changed significantly. It is now ~ 200 V!***
  - ✓ ***Two arcs at each string differential voltage (55 V and 108 V) have been obtained on each coupon. Arc sites preferentially remain as observed during the BOL testing.***
  - ✓ ***The RLC circuit to simulate the primary arc is unchanged from the BOL testing. However, due to the change in threshold voltage the amplitude of the current pulse may be reduced.***

Arc at interim 5th-year test point

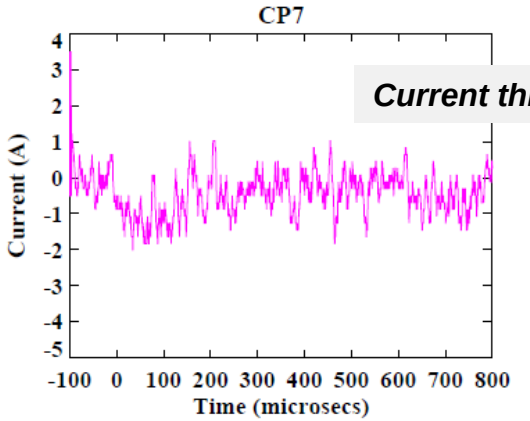
Coupon B: 108V between strings; Temp = 20 C; ΔV ~ 200V



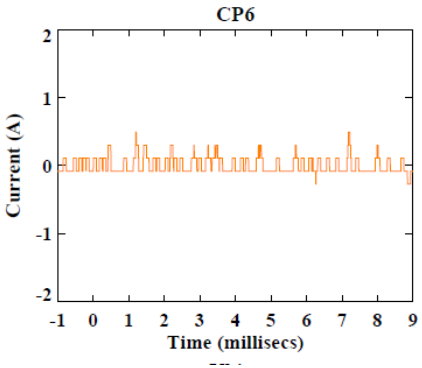
As shown in CP6 and CP2, no activity detected on String-1!

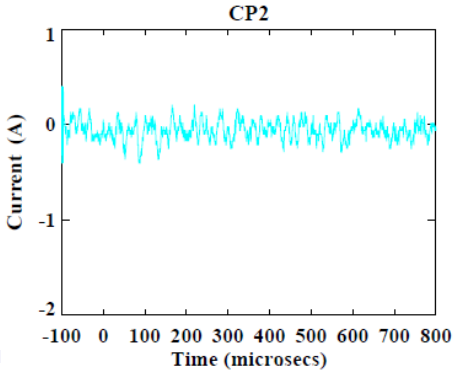


Current through String-2/Cell-2

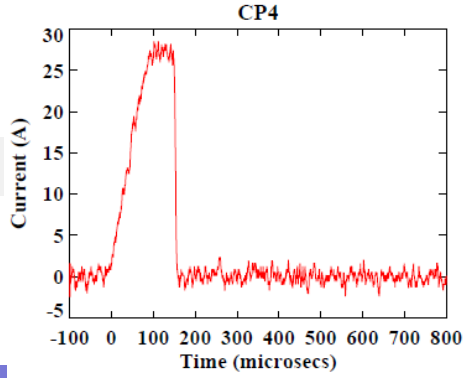


Current through String-2/Cell-1





Primary Arc Current



Key Observations

- ***Post 5th-year combined environmental exposures show hairline cracks in the RTV adhesive grout.***
  - ✓ ***Although an ESD event occurred at a string-to-string (or parallel) gap, no Temporary (or Permanent) Sustained Arc was observed.***
- ***The arc threshold voltage dropped by an order of magnitude after the 5th-year combined environmental exposures.***
  - ✓ ***Our present conjecture is that this is due to the effect of the combined environmental exposures.***
  - ✓ ***If this observation is true in orbit, then the ESD characteristics of the solar array, such as flashover magnitude and arc frequency, can change over the mission life.***

Forward Work

- ***The chamber used for the ESD testing in Phase 2 is also used for ESD testing on another phase of the comprehensive SS/L test campaign involving wire coupons.***
- ***Ion Erosion testing is also slated for this chamber as well.***
- ***Scheduling conflicts are driving completion of the 5th-year ESD testing until this fall (2010).***
- ***10th- and 15th-year ESD testing is currently planned for early and mid 2011, respectively.***

Based on our preliminary observations of our solar array coupon characteristics, there is an apparent need for further research in material properties as a function of combined space environmental exposures.